Fermi National Accelerator Laboratory

FERMILAB-TM-1732

The Behavior of the Tevatron at Energies Greater than 1000 GeV

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April, 1991

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

TM 1732

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Introduction

If, as appears likely, the top quark lies at the upper range of the mass reach of the Tevatron, then increasing the energy of the collider operation could prove to be a crucial factor in the future program together with projected luminosity enhancements. While a significant amount of data exists on individual magnets up to an energy of 1000 GeV, there are no detailed measurements above this value. We focus on the operating range beyond 1000 GeV in an attempt to see whether there is any realistic opportunity to extend the energy range of the Tevatron into this regime.

The proposed modifications to the Tevatron Cryogenic System [1] will provide sufficient cooling to lower the operating temperature of the 1000 superconducting magnets from the present 4.6 - 4.8K (1-ø inlet temperature) down to a range of 3.6 - 3.8K. At this temperature the short sample quench current for the dipole magnets should increase from the present value of ~4000A (900 GeV) up to a level approaching 4800A (1100 GeV).

Increasing the peak current in the dipoles produces some important questions related to possible mechanical effects including catastrophic failure, the change of magnetic field quality, and quench protection problems resulting from the increased stored energy. In this note we shall examine these effects and comment on the existing data on low temperature operation. We have only considered the dipole magnets since the quadrupoles should not limit performance. We have not looked at the interaction region magnets which involve different considerations.

Mechanical Effects

There are two main mechanical effects to be considered: significant coil motion leading to magnet quenches, and inelastic deformation. Since the magnet construction is such that the collared coil assembly is freely supported in the cryostat, then both of these effects pertain to the collared coil assembly only. Motion of the coil results from the large magnetic forces present within the structure of the magnet. These forces are proportional to I^2 and are balanced by an elastic deformation of the coil collar with a magnitude which is also proportional to I^2. Under magnet excitation, the collars become slightly elliptical and the coil moves in both azimuth and radius. While these distortions are in principle calculable, the results depend on the model, material properties, temperature, and other effects; so experimental measurements are very important. The results of a series of such measurements, made with a strain gauge, are given in [2] from which we have taken all of the mechanical deformation data used in this note. The radial distortion along the diameter perpendicular to the field as a function of the dipole current for a single magnet is shown in figure 1, where we have extrapolated the data to 5000A. This change in inner diameter, proportional to I^2 over the range of the measurements, will result in a displacement of 4 mils at 5000A. This is the behavior that would be expected from an elastic displacement of the support structure by Lorentz forces. The validity of the extrapolation to 5000A is discussed below. The change in outer diameter of the coil on the same magnet is shown in figure 2. The motion is very nearly elastic i.e. the motion for current increasing and decreasing is essentially the same and is proportional to the square of the current. A histogram of this data for a sample of 21 magnets is shown in figure 3. The distribution is tightly peaked showing that the construction tolerances are sufficiently well controlled that any conclusions based on single magnet data should be valid for an ensemble of magnets as well. In addition to this radial motion, there is also an azimuthal motion acting to compact the coil. Figure 4 shows data from [2] on this effect; again the motion is elastic over the full range of the measurement and results in a shift of 7 mils when extrapolated to 5000A.

At some excitation, this elastic motion will break down resulting in progressive collar deformation and catastrophic magnet failure. The question is, when does this occur ? On a heuristic level, one can say that even though there is a quadratic dependance with magnet current, since the 5000A points do not involve deformations that are greater than 20% from the well demonstrated 1000 GeV level, then inelastic motion seems improbable up to this point. Finite element analysis of the magnet can provide an estimate of the onset of inelastic deformation of the collared coil assembly. It appears from this type of analysis [3] that the maximum stresses in the collars are produced by the preload. The Lorentz forces change the location in the collars of the maximum stress point but do not increase it significantly. We conclude therefore that there is a large safety factor and no possibility of achieving magnetic fields high enough to inelastically deform the collars.

Magnet quenches arising from azimuthal coil motion is not quite so straight forward. A detailed understanding of magnet training/quenches well below the cable short sample limit still does not exist, but the process is thought to involve mechanical motion of the coils within the collars. When the coil is constructed, it is preloaded in the azimuthal direction to the extent that the elastic forces in the collars are greater than the magnetic ones at high fields; thus the coil remains in contact with the collar and does not move appreciably. The relationship between the forces and fields in the collared coil assembly is a complex problem. A mechanical analysis of this system has been performed by Nicols and Heger from which we have obtained these results. The design preload at room temperature varies across the coil package with a value of 10.5->9.0 kpsi across the inner coil, and 12.0->9.0 across the outer one. During cooldown, there is a preferential shrinkage of the coils with respect to the collars that results in a uniform loss of 1300 psi from both coils. At a magnet excitation of 4800A, the preload on the inner coil is reduced to 6.0->3.0 kpsi while the outer coil stays relatively constant. At this point the vertical motion of the inner coil is ~ 6mils. It would therefore appear that the design magnet will be stable to beyond 4800A. Not all magnets, however, will have exactly the design preload. If the initial room temperature preload is reduced by ~3000 psi, then at 4800A the inner coil becomes unloaded and the coil can start to move. This also happens for a current of ~6000A at the design value. The predicted coil motion at this point is 8.5 mils.

An estimate of the range of preload in the as-built magnets can be obtained from data on the vertical size variation of the collared coil assemblies. Measured relative collared coil sizes at 10 locations along the magnet length for a sample of 20 randomly selected magnets are shown in histogram 1. The distribution is well fitted by a gaussian distribution with a sigma of 2.1 mils. The measurements of Tollestrup and the finite element calculations of Heger are in good agreement in predicting that a variation of 2 mils in the collared coil results in a change in preload of 1000 psi. Assuming that all the magnets lie within ±3 sigma then the magnet to magnet variation of preload will be ±3000 psi. This is just sufficient for the coils to become unloaded at 4800A.

More data relating the effect of azimuthal coil motion to the training behavior of the magnets is given in figure 5 taken from [4]. The vertical axis displays the measured amount of the azimuthal coil motion versus the number of quenches to fully train the magnet for a data set of 81 magnets. Tollestrup interpreted these results by saying that as long as the motion was less than 5 mils, then the collar is supporting the coils. For coil motion of 10 mils and greater, the coils are unclamped and many quenches occur. These data and analysis are in remarkable agreement with the finite element calculations of the previous paragraph (more so since they were made 10 years before the calculations). Azimuthal coil motion for a 1100 GeV excitation as shown in figure 4, predicts a 7 mil change in coil position for that particular magnet. This would place the magnet in the range where this effect is turning on. If the azimuthal coil motion is as reproducible magnet to magnet as the measured radial component, then this is more information indicating that the magnets are starting to enter this regime of persistent quenching with little or no training.

These results and calculations all indicate that around 4800A the dipoles exhibit a threshold in quench behavior. This is not an individual magnet problem (the weak magnet syndrome) but rather a systematic feature of the design. The onset of this behavior should be quite rapid and will signify the effective limit to the machine energy since it will involve many magnets at a similar excitation. While it does not appear possible to accurately predict the absolute value of this energy threshold, the lack of sensitivity to operating temperature provides a strong signature for this effect which will allow a clear indication of the start of the problem in the machine.

Magnetic Field Quality

Possible changes to the magnet field quality in the dipole magnet arise from coil motion and saturation of the iron yoke. There are three components to the coil motion as discussed in the previous section: the radial motion ε_r, the elliptical deformation of the collars ε_ϕ, and the azimuthal motion ∂_i. The effect of these distortions on the magnetic field quality can be qualitatively understood quite simply. The ε_ϕ and ∂_i components compact the coil winding closer to the median plane and make the field stronger, ε_r moves the winding away from the axis causing the field to fall off. There is a cancellation effect between the two motions since the mechanics of the collars connect ε_r and ε_ϕ in a straightforward fashion. As shown in the previous section, these effects are proportional to I^2. Figure 6 taken from [2] shows the calculated change in magnetic field from each component of the motion at 5000A as a function of radius. The cancellation effect is apparent. We have also performed a independent calculation of the magnet field at 5000A comparing the field with and without coil motion . These results are given in table 1 for both a horizontal and vertical offset of up to 2.5 cm. The field variation in the horizontal plane ($\Delta B/B$) is very small, only amounting to 4 parts in 10^5 at its maximum value. The field variation in the vertical plane is somewhat larger than this, rising to 1 part in 10^4 for a 2.5 cm offset, but even at this level will not pose a problem since circulating particles rarely attain this amplitude. It should be pointed out that the vertical magnetic field profile actually improves on an absolute level with this coil motion. For completeness, we have included changes to harmonic field components in standard units in table 2. These results also show no significant variations over this energy range. We conclude that there are no operational problems resulting from changes to the magnetic field arising from coil motion up to a 5000A level.

Saturation of the iron return yoke due to the increased fields will have two main effects; changing the field harmonics (primarily sextupole) due to preferential saturation in the yoke, and modifying the dipole transfer constant which will affect the tracking between the quadrupoles, which do not saturate, and the dipoles running on the same buss. Saturation effects will start to occur when the field in the iron yoke rises above 2T and can produce significant changes to the magnetic field. The situation is different for magnets with the iron yoke close to the coils inside the cryostat (SSC, HERA, UNK - cold iron) and warm iron magnets (Tevatron, UNK - warm iron). In the former case, the bore tube field is strongly influenced by the properties of the iron yoke and saturation effects 'turn-on' quickly at well defined field levels. These magnets can only operate close to their design values since any increase in field strength will result in major changes to the field quality. In the warm iron magnets with the iron outside the cryostat, the effect of the iron on the bore tube field is less as is the peak field in the iron. In this case, it is conceivable that the magnet field can be increased significantly from the design value with acceptable field quality. We have performed a POISSON simulation of the Tevatron dipole to investigate saturation effects. In this model the coil angles are adjusted at low fields (800 GeV) to zero the sextupole multipole of the field; an 'ideal' magnet. The results are shown in figures 7 and 8 where sextupole coefficient and transfer constant are plotted as a function of Tevatron energy. As expected, for the warm iron construction, the magnetic field properties show a relatively weak dependance on peak field. At an excitation corresponding to 1100 GeV, there is ~ 1 extra unit of sextupole (10^{-4} at 2.5 cm) and a transfer constant of 0.9965. Compensating the resulting tune and chromatic effects arising from these field changes at 1100 GeV in the Tevatron will take ~6A in the defocussing sextupole circuit (3A in S_f) and ~3A in the trim quadrupole elements; well within the available capability of the existing circuits. We conclude that saturation effects in the dipoles will not pose a problem up to and beyond an energy of 1100 GeV.

Quench Protection

The Tevatron magnet system must tolerate repeated quenches without damage to the magnets, intermagnet splices, and the long sections of superconducting cable in the bypass regions. A quench is detected in the Tevatron by the quench protection system (QPS) which monitors the resistive voltage across each half cell of magnets. In the case of a quench, the QPS discharges heaters in the dipoles of that particular half cell to drive the magnets normal and distribute the stored energy uniformly across the magnet string.

The criteria for magnet protection is that the energy deposited in any volume of the cable should be insufficient to raise its temperature above a safe value, T_{max}. The integral I^2dt

evaluated in units of 10^6A^2 (MIIT's) uniquely determines the the temperature T at time t in the conductor with well known cable parameters: current, resistivity, density, specific heat and cross sectional area. For the Tevatron magnets at 4kA, a 7 MIIT cable limit was determined to result in a limiting thermal rise of 453K [5]. This T_{max} threshold is due to the melting point of the solder on the staybrite cable. Since in 8 years of operation the Tevatron has not obviously destroyed a magnet due to excess MIITage, it could be argued that this criteria is too conservative. Reference [6] has looked at the worst case quench; a quench outside the coil region which starts in a single cable and propagates in one direction only. The quench detection thresholds for a peak conductor temperature of 450K have been determined. The total MIITs were split into those which accumulate before the quench detection ($t<0$) and those which accumulate after ($t>0$) The results of this calculation giving the two component of the MIITage as a function of current up to 4000A and extrapolated to 5000A, are shown in figure 9, together with the total MIITage and the quench detection voltage threshold needed at each current. The cable parameters used were for 4.2K but do not change significantly for lower temperatures. At 5000A, we obtain $M(t<0)=1.8$, $M(t>0)=5.0$ for a total of 6.8 MIITs when the quench detection threshold is lowered from the present operating level of 0.5V to 0.37V. A reduction in detection threshold of this level should pose few operational problems since magnet test strings and the lo-beta magnets already run with a 0.25 V level. Another result of the increased stored energy is the fact that the peak temperature in the bypass leads will increase by a factor ~1.5 in the adiabatic limit. In the case of a failure of 1 of the 2 bypass SCR switches the single cable temperature rise will be 45°C, the cable rating is 85°C.

Adequately protecting the magnets during quenches at the higher current values may require minor adjustments to the existing equipment but should pose no major problems.

Low Temperature Test Results

There have been low temperature tests performed on two sectors of the Tevatron ring to determine the effect of lower temperature on the magnet quench current [7]. Since each sector contains 180 magnets then these tests are statistically significant although the lowest attainable temperatures with the present equipment is only ~4.0K. The two sectors (A&F)were chosen on the basis of the MTF quench data as they are the best (F) and worst (A) magnet ensembles. In the F-sector tests, the temperature was progressively lowered from a maximum of 4.9K to 4.3K. The quench current for the sector increased from 940 GeV to 1020 GeV which is consistent with the predicted short sample behavior of 130 GeV/K. In order to reach this level, a weak magnet was replaced at 980 GeV.

Two separate tests have been done on A-sector involving a variety of cryogenic compressors on different cryoloops resulting in a series of different temperatures across the magnets. Without changing any elements, the quench current increased from 935 GeV to 1015 GeV as the temperature was lowered by 0.7K. While this is slightly short of the short sample limitation, the magnets were continuing to increase their quench levels as the temperature was lowered. In neither case did the magnets cease to exhibit a dependance on temperature which would indicate that coil motion has started to occur. These tests also indicate that the nominal energy cushion of ~25 GeV between short sample and operating with beam might be reduced at lower temperatures if short sample is not then the limiting factor. The presence of a weak magnet in F-sector emphasizes the point that there are a certain number of bad magnets arising from broken strands, crushed cable, bad splice joints, and the like. MTF and production testing would indicate that this is a relatively small number, it does however represent a unknown distribution. The most noticeable effect in these tests is quenching induced by resistive heating in the splice joints between the magnets. This signature of this effect is quench occurring many seconds into the flattop. While this is not a fundamental property of the magnets it may prove to be the major obstacle to realizing operational higher energies.

Conclusions

The operating energy of the collider program appears not to be limited by mechanical, magnetic or quench protection problems in the magnets. Spontaneous magnet quenches induced by coil motion arising from the Lorentz forces will determine the maximum energy. This regime is determined by the coil preload and should 'turn on' rapidly in many elements at some critical energy which is estimated to be in the vicinity of 1100 GeV. This regime can be identified by a lack of temperature dependance of the quench currents and a critical current threshold. No signs of this type of magnet behavior has been observed in the low temperature tests performed to date.

An operating energy in excess of 1000 GeV can be expected, though much above 1100 GeV is unlikely. The short sample current limitations at 3.8K in the dipoles is well matched to the spontaneous quench regime. Little will be gained by reducing the temperature further than presently envisioned. An unknown distribution of weak magnets exists in the ring, these elements must be identified and replaced. Resistive heating in the splice joints between the magnets appears to be the major problem encountered in the initial tests.

Acknowledgements

The authors wish to thank Patricia Heger for providing the results of the collared coil mechanical analysis, Alvin Tollestrup for general discussions on this subject, Barry Norris for clarification of, and data from, the Tevatron low temperature tests, Karl Koepke for information on the quench protection system and Oleg Zemskov for magnetic field calculations. One of us (OP) would like to thank the Accelerator Division for hospitality shown during his recent visit.

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2) A.V.Tollestrup, Fermilab FM-331, 1980.

3) P. Heger, private communications, March 1991.

4) A.V.Tollestrup, Fermilab TM-1251, 1984.

5) K.Koepke, P.Martin, Fermilab UPC-155, 1982.

6) K.Koepke, internal memo, February 1991.

7) J.D.Fuerst, Fermilab TM-1677, 1990.

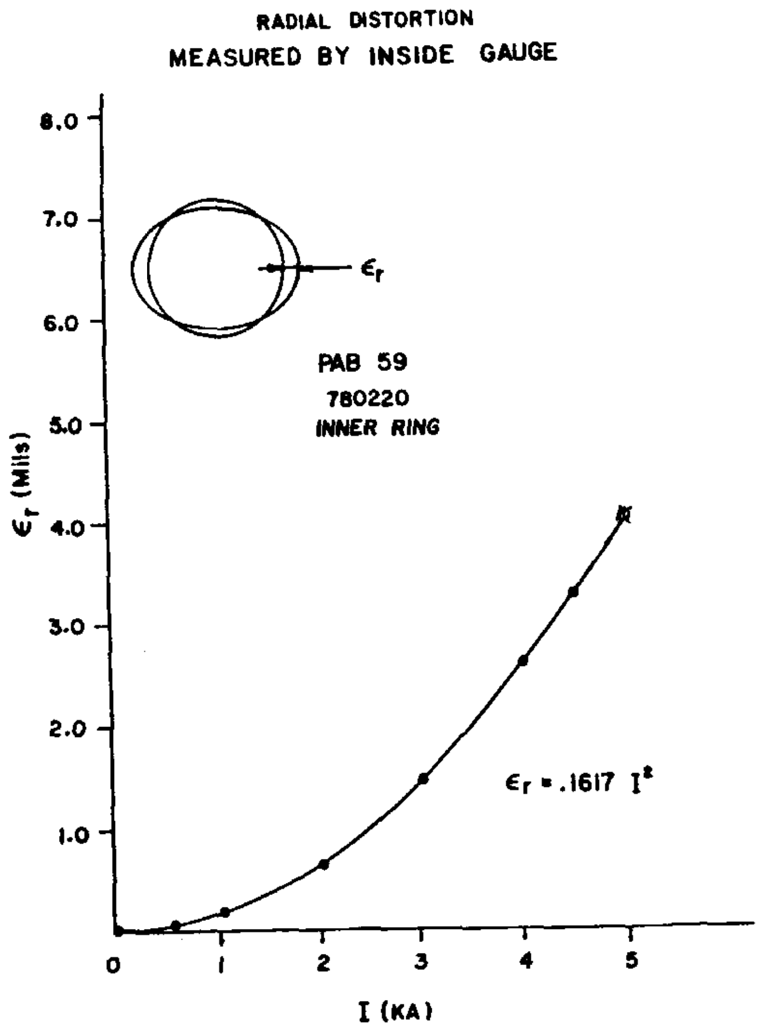

RADIAL DISTORTION
MEASURED BY INSIDE GAUGE
PAB 59
780220
INNER RING
ϵ_r
$\epsilon_r = .1617\ I^2$
ϵ_r (Mils)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1
2
3
4
5
I (KA)

Fig. 1

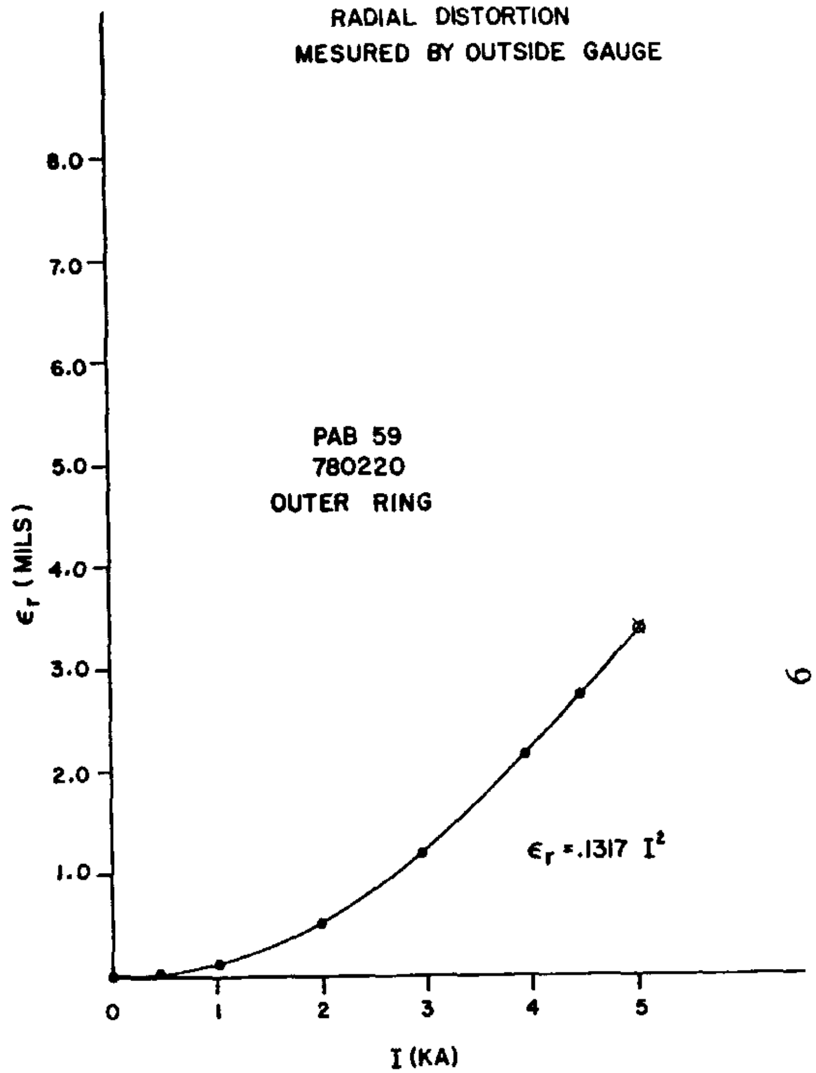

RADIAL DISTORTION
MESURED BY OUTSIDE GAUGE
PAB 59
780220
OUTER RING
$\epsilon_r = .1317\ I^2$
ϵ_r (MILS)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1
2
3
4
5
I (KA)

Fig. 2

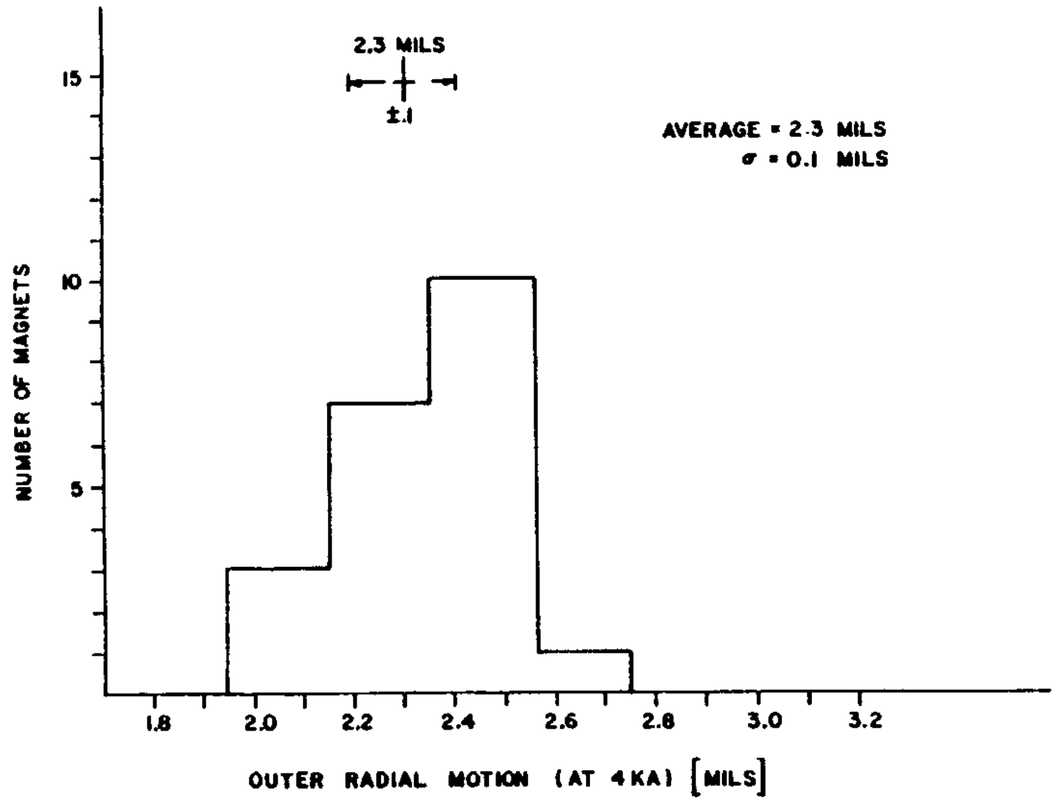

2.3 MILS
±.1
AVERAGE = 2.3 MILS
σ = 0.1 MILS
NUMBER OF MAGNETS
15
10
5
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
OUTER RADIAL MOTION (AT 4 KA) [MILS]

Fig. 3

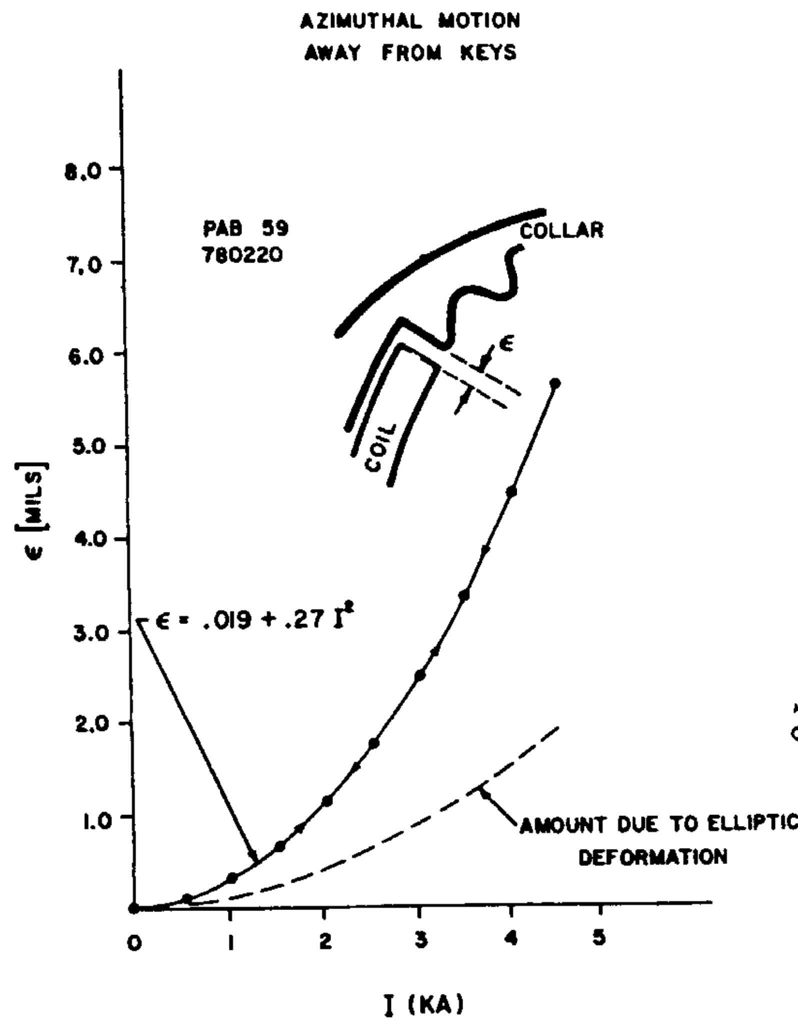

AZIMUTHAL MOTION
AWAY FROM KEYS
PAB 59
780220
COLLAR
COIL
ε
ε = .019 + .27 I²
AMOUNT DUE TO ELLIPTIC
DEFORMATION
ε [MILS]
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1
2
3
4
5
I (KA)

Fig. 4

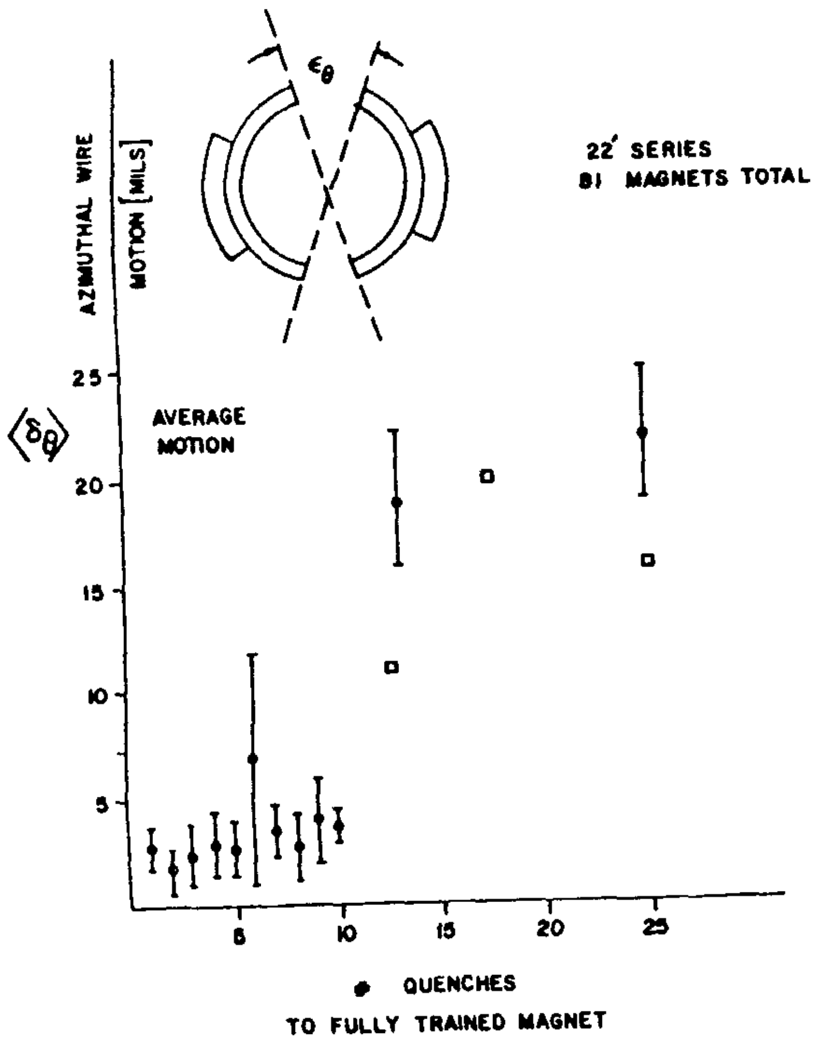

AZIMUTHAL WIRE
MOTION [MILS]
$\langle\delta_\theta\rangle$
ϵ_θ
22′ SERIES
81 MAGNETS TOTAL
AVERAGE
MOTION
25
20
15
10
5
5
10
15
20
25
QUENCHES
TO FULLY TRAINED MAGNET

Fig. 5

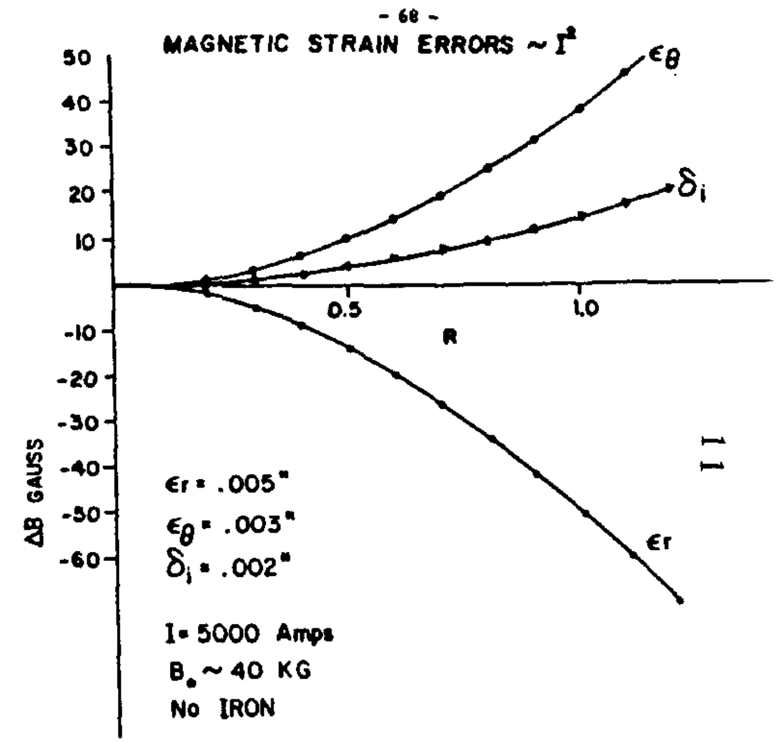

- 68 -
MAGNETIC STRAIN ERRORS ~ I^2
ϵ_θ
δ_i
ϵ_r
50
40
30
20
10
-10
-20
-30
-40
-50
-60
0.5
1.0
R
ΔB GAUSS
ϵ_r = .005"
ϵ_θ = .003"
δ_i = .002"
I = 5000 Amps
B_o ~ 40 KG
No IRON

Fig. 6

Figure 7

Sextupole coefficient v's magnet excitation

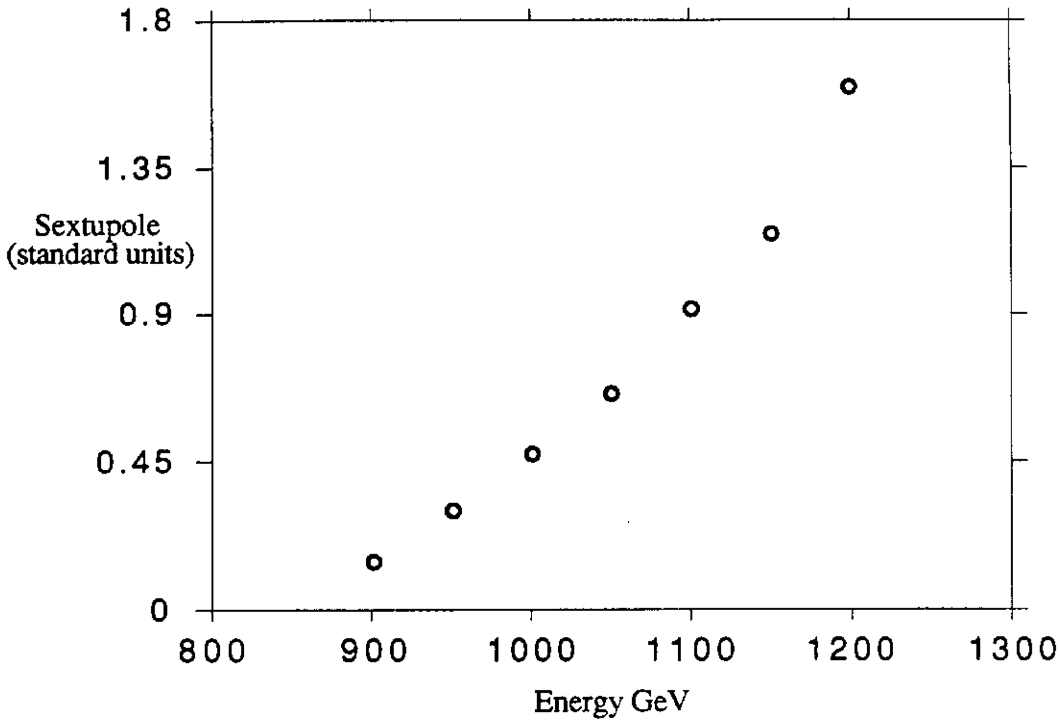
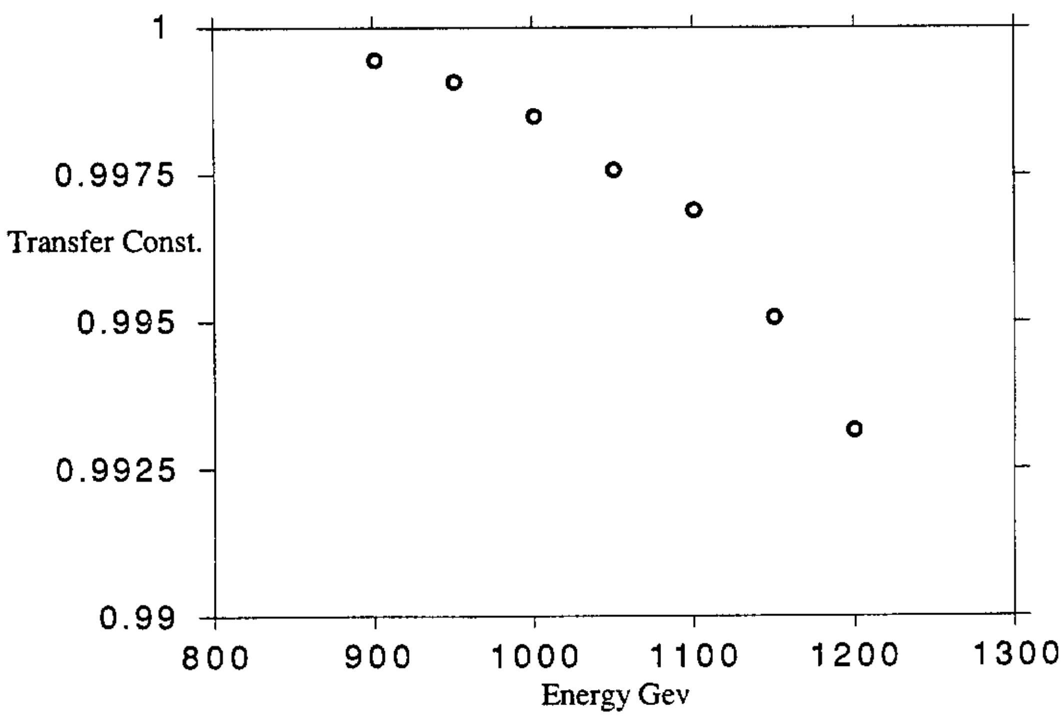
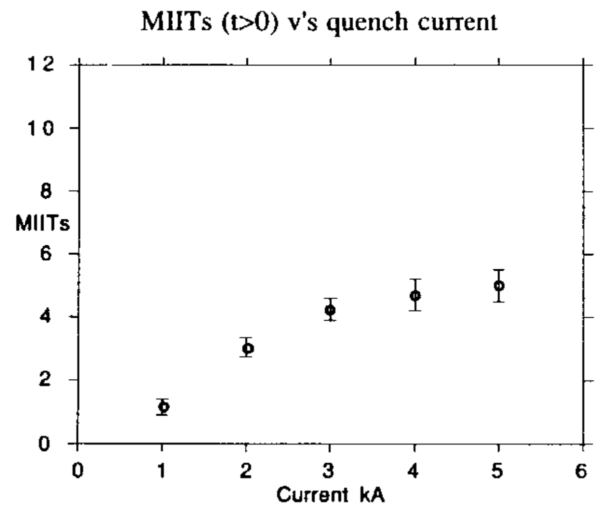


Figure 8

Transfer Constant v's magnet excitation




MIITs (t>0) v's quench current
MIITs
Current kA
0
2
4
6
8
10
12
1
3
5

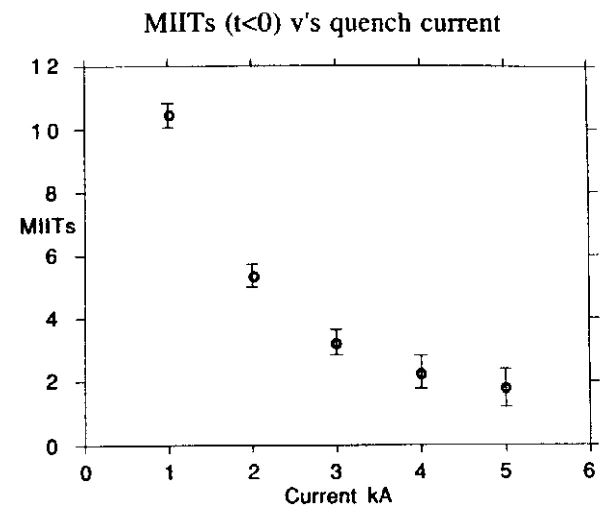
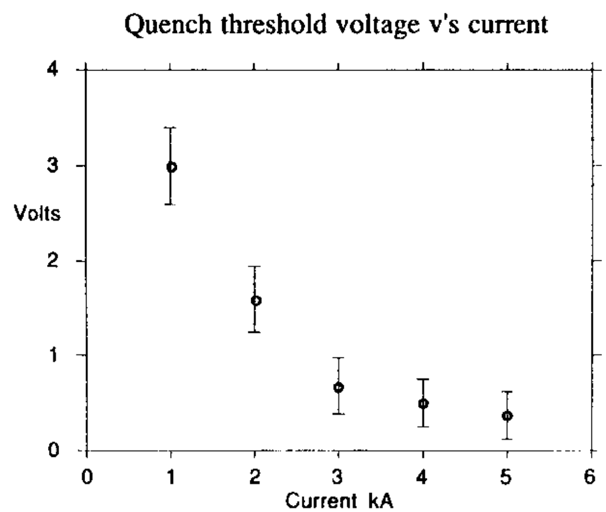
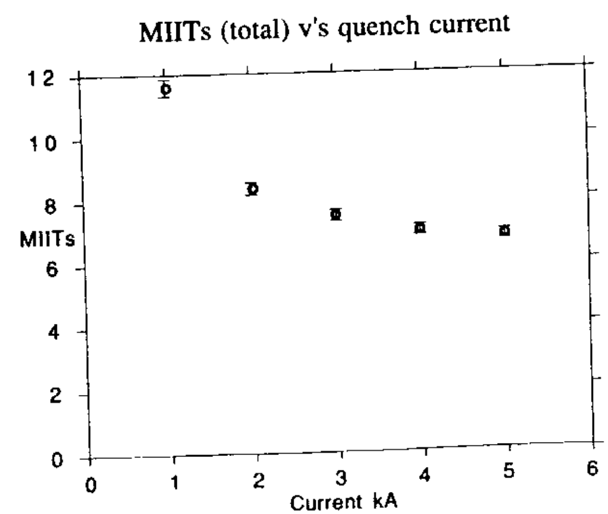

MIITs (t<0) v's quench current
MIITs
Current kA
0
2
4
6
8
10
12
1
3
5

Fig. 9


Quench threshold voltage v's current
Volts
Current kA
0
1
2
3
4
5
6


MIITs (total) v's quench current
MIITs
Current kA
0
2
4
6
8
10
12
1
3
5

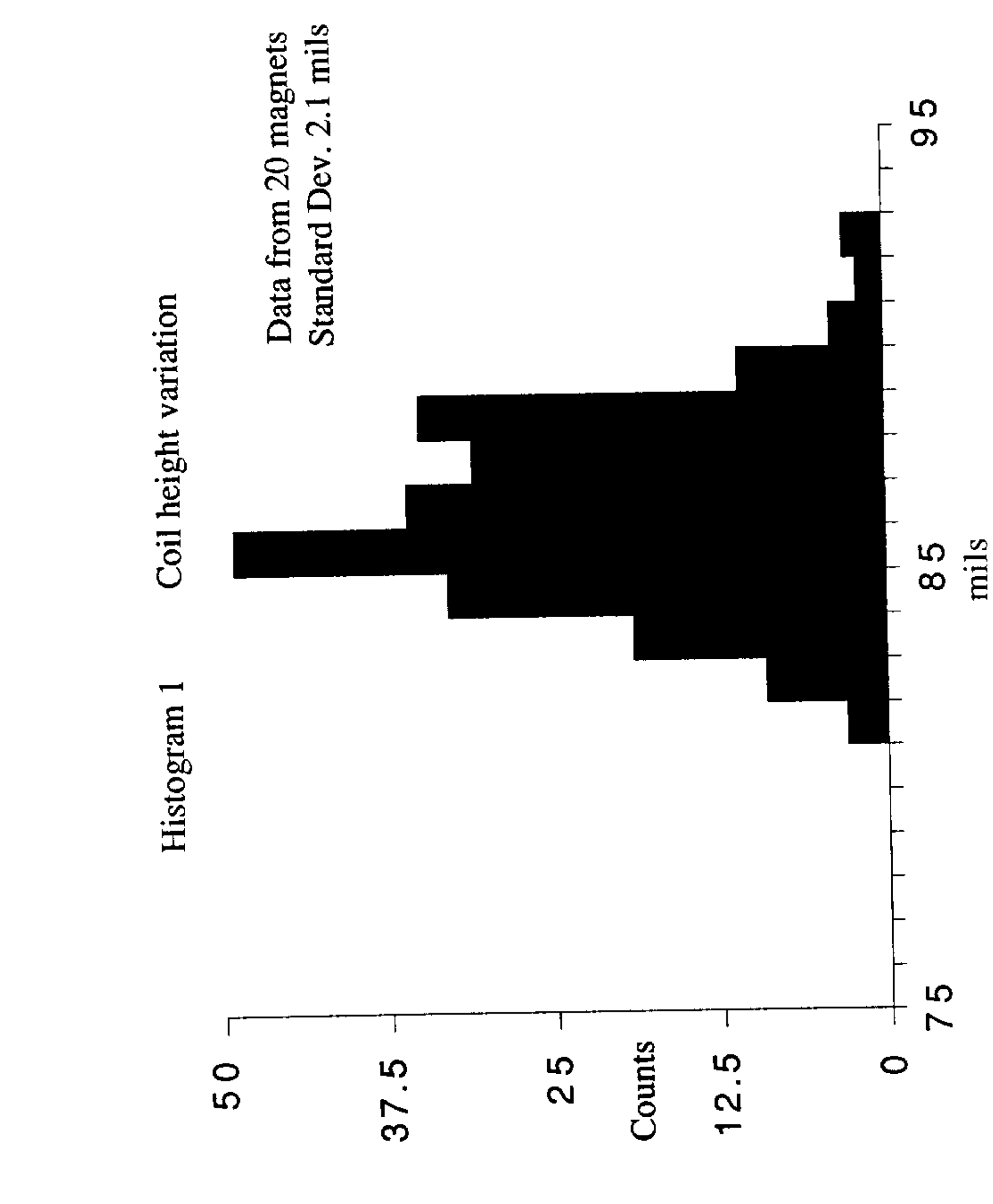

Histogram 1
Coil height variation
Data from 20 magnets
Standard Dev. 2.1 mils
50
37.5
25
12.5
0
Counts
75
85
95
mils

Table 1: Field Variation due to coil motion at 5000A

ΔX cm	By (kG) no coil motion	By (kG) with coil motion	ΔBy (G)
0.00	49.625	49.643	18
0.25	49.626	49.644	18
0.51	49.629	49.646	17
0.76	49.634	49.650	16
1.02	49.642	49.656	14
1.27	49.652	49.664	12
1.52	49.665	49.674	9
1.78	49.682	49.687	5
2.03	49.700	49.703	3
2.29	49.720	49.719	-1
2.54	49.739	49.734	-5

ΔY cm	By (kG) no coil motion	By (kG) with coil motion	ΔBy (G)
0.00	49.625	49.643	18
0.30	49.624	49.642	18
0.60	49.619	49.639	20
0.90	49.613	49.634	21
1.20	49.603	49.628	25
1.50	49.590	49.619	29
1.80	49.572	49.607	35
2.10	49.541	49.583	42
2.40	49.482	49.533	51

Table 2 : Field Harmonics variation due to coil motion at 5000A

Harmonic Coefficient	no coil motion	with coil motion	Δ coeff
b0	49.625	49.643	18
b2	2.03*10E-3	1.51*10E-3	5.2*10E-4
b4	7.17*10E-4	6.72*10E-4	4.5*10E-5
b6	-1.00*10E-4	5.3*10E-5	-1.5*10E-4
b8	-2.5*10E-4	-1.8*10E-4	-7.0*1-E-5
b10	-9.7*10E-5	-2.2*10E-4	1.2*10E-4